Charting the Higgs potential with pair-production of Higgs bosons at the ATLAS experiment

Canadian Association of Physicists Congress, May 27th-31st 2024

Marco Valente
Particle Physics department
TRIUMF, Canada’s particle accelerator centre
marco.valente@cern.ch
Introduction (1)
What is the Higgs boson and why its discovery (2012) was important

- Higgs boson: **massive scalar particle**
generated by the spontaneous breaking
of the electroweak gauge symmetry.

- Ok… but what does this mean? 😊

  - Take the massless SM lagrangian $\mathcal{L}^{SM}$, add a scalar particle and a “a mexican hat” potential:

  $$V(\phi^\dagger \phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

- Around the new potential minimum, electroweak bosons (W/Z) and fermions acquire masses. A massive scalar appears (the Higgs boson).

- This works surprisingly well (so far)! **All observed couplings** (W,Z,b,t,τ) are consistent with the SM Higgs mechanism!
Is this the end of the story?
Have we understood everything about the Higgs?

• Simple answer: **No!**

• The simple existence of the Higgs in the SM is **really unique and puzzling:**
  • Are there **more Higgs bosons**?
  • Why is the **Higgs mass so small**?
  • Is it really a **Mexican hat potential shape or something else**?

This is what we experimentally know about the Higgs potential

Many different potential shapes could explain the same physics we see today!

\[
V(H) \approx \begin{cases} 
-m^2H^\dagger H + \lambda(H^\dagger H)^2 + \frac{\mu^2}{2}(H^\dagger H)^4, \\
-a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), \\
\lambda(H^\dagger H)^2 + c(H^\dagger H)^3 \log \sqrt{H^\dagger H}, \\
-e^2\sqrt{H^\dagger H} + m^2H^\dagger H, 
\end{cases}
\]

arxiv:1907.02078
The Higgs potential in the history of the universe
Electroweak baryogenesis and vacuum metastability

• The Higgs potential is **deeply related to the baryogenesis problem.**
  
  • A potential shape beyond the SM could explain the overabundance of matter in the universe (EWK baryogenesis)!

• Also, important question about the **stability of our current universe vacuum state!**
The Higgs potential in the history of the universe
Electroweak baryogenesis and vacuum metastability

• The Higgs potential is **deeply related to the baryogenesis problem.**
  
  • A potential shape beyond the SM could explain the overabundance of matter in the universe (EWK baryogenesis)!

• Also, important question about the **stability of our current universe vacuum state!**
The Higgs potential in the history of the universe
Electroweak baryogenesis and vacuum metastability

• The Higgs potential is deeply related to the baryogenesis problem.

• A potential shape beyond the SM could explain the overabundance of matter in the universe (EWK baryogenesis)!

• Also, important question about the stability of our current universe vacuum state!

Current measurements suggest that we live in a metastable universe that will decay in future!
Measuring the Higgs potential is critical to fully understand how the universe started... and also how it will finish.
But so... how can we measure the Higgs potential?
How to measure the Higgs potential

Multiple-Higgs events

We need to access the $\lambda$ parameter of the Higgs potential.

\[
V(h) = -\mu^2 |\phi|^2 + \lambda |\phi|^4 \approx \frac{1}{2} m_h^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 + \ldots
\]
How to measure the Higgs potential

Multiple-Higgs events

We need to access the $\lambda$ parameter of the Higgs potential.

$$V(h) = -\mu^2 |\phi|^2 + \lambda |\phi|^4 \approx \frac{1}{2} m_h^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 + \ldots$$

Tells us where the minimum of the potential is

$$m_H = \sqrt{2\lambda v} \approx 125 \text{ GeV} \text{ means } \lambda_{SM} \approx 0.13$$
How to measure the Higgs potential

Multiple-Higgs events

We need to access the $\lambda$ parameter of the Higgs potential.

\[ V(h) = -\mu^2 |\phi|^2 + \lambda |\phi|^4 \approx \frac{1}{2} m_h^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 + \ldots \]

Tells us where the minimum of the potential is

\[ \Rightarrow m_H = \sqrt{2\lambda v} \approx 125 \text{ GeV} \text{ means } \lambda_{SM} \approx 0.13 \]

Access to $\lambda$ through 3-Higgs interactions

We generally look more at $\kappa_\lambda$ rather than $\lambda$ directly

\[ \kappa_\lambda \equiv \frac{\lambda}{\lambda_{SM}} \]
How to measure the Higgs potential

Multiple-Higgs events

We need to access the $\lambda$ parameter of the Higgs potential.

$$V(h) = -\mu^2 |\phi|^2 + \lambda |\phi|^4 \approx \frac{1}{2} m_h^2 h^2 + \lambda v h^3 + \frac{1}{4} \lambda h^4 + \ldots$$

Tells us where the minimum of the potential is

$$\Rightarrow m_H = \sqrt{2\lambda v} \approx 125 \text{ GeV} \text{ means } \lambda_{SM} \approx 0.13$$

Quadrilinear Higgs self-coupling

Out of the reach of (HL)-LHC (and even most of future collider scenarios)

We generally look more at $\kappa_\lambda$ rather than $\lambda$ directly

$\kappa_\lambda \equiv \frac{\lambda}{\lambda_{SM}}$
HH production at the LHC
Non-resonant HH production

Gluon-gluon fusion (ggF)
- Destructive interference leads to small cross-section:
  \[ \sigma_{ggF} = 31.05 \text{ fb} \]
  1 HH event every 1000 single-H events!

Vector-boson fusion (VBF)
- Signature: 2 Higgs + 2 quarks close to the LHC proton beams.
- Access to \( \kappa_\lambda \), but also to VVHH process (never measured!) which could provide test of SM unitarity via measurement of \( k_{2V} \).
- Very tiny cross-section:
  \[ \sigma_{VBF} = 1.72 \text{ fb} \]
The HH final states

- With $\sigma(HH) \approx 31 \text{ fb}$ and $L^{int} = 139 \text{ fb}^{-1}$, ~4k HH events produced in the LHC Run 2.

- Maximal sensitivity requires multiple analysis channels targeting different decays.

<table>
<thead>
<tr>
<th>Higher BR</th>
<th>bb</th>
<th>WW</th>
<th>$\tau\tau$</th>
<th>ZZ</th>
<th>$\gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>bb</td>
<td>33%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WW</td>
<td>25%</td>
<td>4.6%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>7.4%</td>
<td>2.5%</td>
<td>0.39%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZZ</td>
<td>3.1%</td>
<td>1.2%</td>
<td>0.34%</td>
<td>0.076%</td>
<td></td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>0.26%</td>
<td>0.10%</td>
<td>0.029%</td>
<td>0.013%</td>
<td>0.0005%</td>
</tr>
</tbody>
</table>

First Higgs decay

Second Higgs decay

Most sensitive ATLAS channels covered in this talk.
HH detection at ATLAS
To observe $HH$ decaying to $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$ channels we need to identify b-quarks, $\tau$-leptons and photons.
HH final state reconstruction

To observe $HH$ decaying to $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$ channels we need to identify $b$-quarks, $\tau$-leptons and photons.

- **b-jets**: collimated spray of particles containing a displaced vertex (B-hadron decay).
- Machine Learning **b-tagging algorithms** for identification.

Marco Valente
Centre
Physics department
TRIUMF, Canada's particle accelerator Centre

CAP 2024 [27-31 Mar 2024]
To observe $HH$ decaying to $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$ channels we need to identify $b$-quarks, $\tau$-leptons and photons.

- **b-jets**: collimated spray of particles containing a displaced vertex (B-hadron decay).
- Machine Learning **b-tagging algorithms** for identification.
- **Photons**: isolated ECAL energy deposit without associated track.
To observe $HH$ decaying to $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$ channels we need to identify $b$-quarks, $\tau$-leptons and photons.

- **b-jets**: collimated spray of particles containing a displaced vertex (B-hadron decay).
- **Machine Learning b-tagging algorithms** for identification.
- **Photons**: isolated ECAL energy deposit without associated track.
- **Taus**: $\nu_\tau$ plus
  1. **Hadronic $\tau$ ($\tau_{\text{had}}$)**: jet with low number of tracks identified with $\tau$ tagger.
  2. **Leptonic $\tau$ ($\tau_{\text{lep}}$)**: muon ($\mu$) or electron ($e$)
HH final state reconstruction

To observe $HH$ decaying to $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$ channels we need to identify $b$-quarks, $\tau$-leptons and photons.

- **b-jets**: collimated spray of particles containing a displaced vertex (B-hadron decay).
- Machine Learning **b-tagging algorithms** for identification.
- **Photons**: isolated ECAL energy deposit without associated track.
- **Taus**: $\nu_\tau$ plus
  1. **Hadronic $\tau$ ($\tau_{\text{had}}$)**: jet with low number of tracks identified with $\tau$ tagger.
  2. **Leptonic $\tau$ ($\tau_{\text{lep}}$)**: muon ($\mu$) or electron ($e$)
$HH \rightarrow b\bar{b}\gamma\gamma$ analysis (139 fb$^{-1}$)

Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST
HH → b\bar{b}γγ analysis (1)

Analysis selection and categories

- Very tiny HH BR (0.26%), but excellent acceptance (γγ triggers) and low backgrounds.

- Selection: 2 photons + 2 b-jets (77% eff.)
  - BDTs used to separate backgrounds and signals.

- Categories: 7 regions split in $m^*_{bb\gamma\gamma}$ (350 GeV) and BDT output to enhance sensitivity to signal.

\[ m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250 \text{ GeV} \]
**HH → b\bar{b}γγ analysis (2)**

Background estimation and results

**Final observation:** simultaneous likelihood fit of $m_{γγ}$ in 7 categories.

- **Main backgrounds:** $γγ + \text{jets}$ and SM $H → γγ$.

- **No significant excess** above SM prediction.
$HH \to b \bar{b} \tau^+ \tau^-$ analysis (139 fb$^{-1}$)
**HH → b\bar{b}ττ analysis (1)**

Event selection and analysis categories

- **Good trade between HH BR (7.3%) and moderate background.**

- **Selection:** 2 b-jets (77% eff.) and 2 \(τ\)-leptons (\(τ_{\text{had}}\) and \(τ_{\text{lep}}\))

  - **9 categories:** split in \(τ\) decay mode (had-had, lep-had) and HH production mode (ggF VBF).

- **BDT outputs in categories are simultaneously fit** to separate background and signals.

- **No significant excess observed.**
$HH \rightarrow b\bar{b}b\bar{b}$ analysis (126 fb$^{-1}$)
**HH → b\bar{b}b\bar{b} analysis (1)**

Selection and analysis categories

- **Largest HH BR** (34%), but large multi-jet background and challenging jet-pairing combinatorics.

- **Selection:** at least 4 b-jets (77% eff.)
  - VBF selection: two additional jets close to the beam (|\Delta \eta_{jj}| > 3).

- **Background estimation:** fully data-driven with machine-learning-assisted ABCD method.

- **Categories:** 6 for ggF and 2 for VBF to enhance signal sensitivity.

- **No significant excess** observed.
Combining everything together...
Higgs self-coupling constraints

Allowed $\kappa_\lambda$ ranges

- **What did we learn** about the Higgs self-coupling?
- **$\kappa_\lambda$ scan**: upper-limits on $\sigma_{HH}$ assuming signal normalisation and kinematic at each value of $\kappa_\lambda$

- Observed allowed $\kappa_\lambda$ range is measured to be $-0.6 < \kappa_\lambda < 6.6$
- For the standard model point, combined observed (expected) 95% CL upper limit: $\mu_{SM}^{95\%} = 2.4 (2.9)$!

Very close to the SM signal! We are getting close to regions with exciting BSM physics scenarios!
And for VBF ($\kappa_{2V}$)?
Boosted VBF $HH \rightarrow b\bar{b}b\bar{b}$ analysis (139 fb$^{-1}$)

arXiv:2404.17193
Boosted VBF $HH \rightarrow b\bar{b}b\bar{b}$

Analysis strategy

- Extremely high sensitivity to $k_{2V}$ variations due to kinematic boost of Higgs bosons.
  - Less statistics, but also much less backgrounds!

- $H \rightarrow b\bar{b}$ identified through dedicated machine-learning double-$b$ tagger (ATL-PHYS-PUB-2020-019).

- Selection:
  - 2 large-radius jets tagged as $H \rightarrow b\bar{b}$ (60% eff.)
  - 2 small-radius jets close to the beam ($|\Delta\eta(j,j)| > 3$)

- Background estimation: fully data-driven ABCD method.

- No excess above SM prediction.

arXiv:2404.17193
Boosted VBF $HH \rightarrow b\bar{b}b\bar{b}$

**k2V limits**

- At 95% CL: $\kappa_{2V} \in [0.52,1.52]$ (boosted-only)!
  - Much more sensitive than resolved $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ ($\kappa_{2V} \in [0.1,2.0]$)!
  - Even more **sensitive than expected sensitivity at the HL-LHC** ($3000 \text{ fb}^{-1}$)! A huge step forward in just a couple of years!

---

**Boosted VBF $HH \rightarrow b\bar{b}b\bar{b}$ (140 fb$^{-1}$)**

**Resolved $HH \rightarrow b\bar{b}b\bar{b}$ at HL-LHC (3000 fb$^{-1}$)**
So no unexpected Higgs self-coupling values for now.

Can we improve the precision in future?
Run 3 ATLAS improvements

More data, better reconstruction and triggers

- Expect a **large number of improvements** by the end of Run 3 (2022-2025).
  - **More data** (150 – 250 fb\(^{-1}\) in Run 3) and +10% \(\sigma(HH)\) with \(\sqrt{s} = 13.6\) TeV
  - **b-tagging largely improved** with Graph Neural Networks!
  - **Triggers significantly improved** (e.g. asymmetric \(HH \rightarrow b\bar{b}b\bar{b}\) triggers)!

\[
s = 13.6\ \text{TeV}
\]

**Charting the Higgs potential with pair-production of Higgs bosons at the ATLAS experiment**

CAP 2024 [27-31 Ma7 2024]
Conclusion and prospects

- The Higgs sector is **UNIQUE** and still largely unexplored!
  - Shape of the **Higgs potential essential** to fully understand EWSB and the evolution of the universe.
- **HH searches** at the (HL-)LHC are currently the **best tool** to constrain $V(\phi)$:
  - Huge improvements on $\kappa_\lambda$ and $\kappa_{2V}$ constraints achieved with Run 2 ATLAS dataset.
  - $5\sigma$ discovery achievable at the HL-LHC (ATLAS+CMS).
  - More improvements are expected for Run 3 (more data, better triggers, better physics object identification, etc.).

If something is unexpected in the Higgs potential, Run 3 might already reveal this to us!

The human factor is important!
Thank you for your attention!

STAY TUNED
COMING SOON
Backup
Challenges of HH production at the LHC
The unbearable lightness of HH

Not only small cross-section, **but also complex signal kinematic** due to diagram interference!

Impact of $\kappa_\lambda$ more visible in soft part (i.e. low $p_T$) of the $m_{HH}$ spectrum

Access low $m_{HH}$ events is hard due to soft Higgs kinematics!
Updated HL-LHC projections for HH

• Assuming Run 2 detector performance and expected reduction of systematics, statistical evidence \((3.4\sigma)\) is expected for SM HH \((\kappa_\lambda = 1)\) with 3000 fb\(^{-1}\).

• \(\kappa_\lambda\) constrained to \([0.5,1.6]\) at 68% CL.

• Reduction of systematic uncertainties could bring us close to discovery \((4.9\sigma\text{ with stat. only})\). And we still have to combine with CMS!

---

**ATLAS Preliminary**

\(\sqrt{s} = 14\text{ TeV}\)

\(HH \rightarrow b\bar{b}\gamma\gamma + b\bar{b}\tau^+\tau^- + b\bar{b}b\bar{b}\)

Projection from Run 2 data

Asimov data \((\kappa_\lambda = 1)\)

- No syst. unc.
- Baseline
- Theoretical unc. halved
- Run 2 syst. unc.

---

\(-2\Delta\ln(L)\)

\(\sqrt{s} = 14\text{ TeV}, 3000\text{ fb}^{-1}\)

Non-resonant HH

Baseline

Asimov data \((\kappa_\lambda = 1)\)

- \(b\bar{b}\tau^+\tau^-\)
- \(b\bar{b}\gamma\gamma\)
- \(b\bar{b}b\bar{b}\)
- Combined

---

Marco Valente

Physics Department, TRIUMF, Canada’s particle accelerator Centre
Updated HL-LHC projections for HH

**ATLAS** Preliminary

$\sqrt{s} = 14$ TeV, 3000 fb$^{-1}$

$HH \rightarrow b\bar{b}\gamma\gamma + b\bar{b}\tau^+\tau^- + b\bar{b}b\bar{b}$

Projection from Run 2 data

Asimov data ($\kappa_\lambda$)

- No syst. unc.
- Baseline
- Theoretical unc. halved
- Run 2 syst. unc.

**Diagram Description**

The diagram illustrates the significance as a function of $\kappa_\lambda$ for the $HH \rightarrow b\bar{b}\gamma\gamma + b\bar{b}\tau^+\tau^- + b\bar{b}b\bar{b}$ process at the ATLAS experiment. The significance is calculated with $\sqrt{s} = 14$ TeV and an integrated luminosity of 3000 fb$^{-1}$. The projection from Run 2 data is shown with different assumptions for systematic uncertainties, including baseline, theoretical uncertainty halved, and Run 2 systematic uncertainty.
Background estimation

- **Background**: QCD multijet (90%) and $t\bar{t}$ (10%) estimated using a **fully data-driven** method.
  - **Machine-learning algorithm learns weight** $w(x)$, where $x$ are different event kinematic variables, to **reweight** CR1-2b into CR1-4b events
  - $w(x)$ **applied to** SR-2b to obtain SR-4b background estimation.

- Alternative $w'(x)$ from CR2 used to estimate systematics uncertainties.
$HH \rightarrow b\bar{b}\tau\tau$ analysis

Analysis categories

- **STT + DTT**
  - Event selection
  - VBF candidate: ≥ 2 extra jets
    - m$_{HH}$
      - Low-m$_{HH}$ category
      - High-m$_{HH}$ category
      - VBF-like
    - ggf-like
      - < 300 GeV
      - > 300 GeV
  - Categorisation BDT

- **SLT**
  - Event selection
    - VBF candidate: ≥ 2 extra jets
      - m$_{HH}$
        - Low-m$_{HH}$ category
        - High-m$_{HH}$ category
        - VBF category
      - ggf-like
        - < 300 GeV
        - > 300 GeV
  - Categorisation BDT

- **LTT**
  - Event selection
    - VBF candidate: ≥ 2 extra jets
      - m$_{HH}$
        - Low-m$_{HH}$ category
        - High-m$_{HH}$ category
        - VBF category
      - ggf-like
        - < 300 GeV
        - > 300 GeV
  - Categorisation BDT

- **SLT + DLT**
  - Event selection
    - $T_{had\,had\,bb}$

- **CR**
  - STT: single $T_{had\,vs\,had}$ triggers
  - DTT: di-$T_{had\,vs\,had}$ triggers
  - SLT: single lepton triggers
  - LTT: lepton+$T_{had\,vs\,had}$ triggers
  - DLT: di-lepton triggers
**HH → b¯bττ analysis**

Background estimation and results

- **Dominant backgrounds:** $t\bar{t}$ and $Z(\rightarrow \tau\tau)$+bb/bc/cc)

- **Final observation:** binned fit of MVA scores in all 9 categories.

- **No significant excess** above SM prediction observed.
SM cross-section upper limits

Results

• Statistical **combination maximises sensitivity** to SM (and BSM) HH production

\[ \mu_{HH} = \frac{\sigma^{obs}(pp \rightarrow HH)}{\sigma^{SM}(pp \rightarrow HH)} \]

Phys. Lett. B 843 (2023) 137745

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 126-139 \text{ fb}^{-1} \)

\( c_{99F}^{SM} + vBF(HH) = 32.7 \text{ fb} \)

<table>
<thead>
<tr>
<th>Signal</th>
<th>Obs.</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b\bar{b}\gamma\gamma )</td>
<td>4.2</td>
<td>5.7</td>
</tr>
<tr>
<td>( b\bar{b}\tau^+\tau^- )</td>
<td>4.7</td>
<td>3.9</td>
</tr>
<tr>
<td>( b\bar{b}b\bar{b} )</td>
<td>5.4</td>
<td>8.1</td>
</tr>
<tr>
<td>Combined</td>
<td>2.4</td>
<td>2.9</td>
</tr>
</tbody>
</table>

95% CL upper limit on HH signal strength \( \mu_{HH} \)

Getting very close to the SM (\( \mu_{HH} = 1 \))

Currently observing \( \mu_{HH}^{95\% \text{ CL}} < 2.4 \)

**Previous result (36 fb\(^{-1}\))**

- Expected: 26xSM
  - Observed: 20.3xSM
- Expected: 15xSM
  - Observed: 12.5xSM
- Expected: 20.7xSM
  - Observed: 12.9xSM
- Expected: 10xSM
  - Observed: 6.9xSM

Large improvement (x3.5) thanks to **luminosity**, better **reconstruction** (b-jet, \( \tau \)) and **analysis improvements**
The evolution of the Higgs potential

- BSM effect in the Higgs potential could explain the matter-antimatter asymmetry of the universe.

- BSM physics acting on the Higgs potential would enable EWK bubble nucleation.

Slow second order phase transition

Strong first order phase transition

EWK baryogenesis
**HH → b¯bγγ analysis**

Additional material

Figure 4: Reconstructed four-body mass for $m_X = 300$ GeV and $m_X = 500$ GeV resonant signal benchmarks and for the $γγ$+jets background. Dashed lines represent the distribution of $m_{b¯bγγ}$ while solid lines represent the distribution of $m^*_{b¯bγγ}$, defined in Section 4.2.1. Distributions are normalized to unit area.
HH combined and separate likelihoods

\[ \text{arxiv:2211.01216} \]
Single-Higgs constraints to $\kappa_\lambda$ and $\kappa_t$

Results

- **Combination with ttH** also allow to constrain HH box-diagram effects via direct measurement of $\kappa_t$
Updated projections for HL-LHC

**ATLAS-PHYS-PUB-2022-053**

**Charting the Higgs potential with pair-production of Higgs bosons at the ATLAS experiment**

**CAP 2024 [27-31 Mar 2024]**

### Table: Significance and Combined Signal Strength Precision

<table>
<thead>
<tr>
<th>Uncertainty scenario</th>
<th>$b\bar{b}\gamma\gamma$</th>
<th>$b\bar{b}\tau^+\tau^-$</th>
<th>$b\bar{b}b\bar{b}$</th>
<th>Combination</th>
<th>Combined signal strength precision [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No syst. unc.</td>
<td>2.3</td>
<td>4.0</td>
<td>1.8</td>
<td>4.9</td>
<td>-21/+22</td>
</tr>
<tr>
<td>Baseline</td>
<td>2.2</td>
<td>2.8</td>
<td>0.99</td>
<td>3.4</td>
<td>-30/+33</td>
</tr>
<tr>
<td>Theoretical unc. halved</td>
<td>1.1</td>
<td>1.7</td>
<td>0.65</td>
<td>2.1</td>
<td>-47/+48</td>
</tr>
<tr>
<td>Run 2 syst. unc.</td>
<td>1.1</td>
<td>1.5</td>
<td>0.65</td>
<td>1.9</td>
<td>-53/+65</td>
</tr>
</tbody>
</table>

**Figure: ATLAS Preliminary**

$\sqrt{s} = 14$ TeV, 3000 fb$^{-1}$

Non-resonant HH

Baseline

Asimov data ($\kappa_\Lambda = 1$)

- $b\bar{b}\tau^+\tau^-$
- $b\bar{b}\gamma\gamma$
- $b\bar{b}b\bar{b}$
- Combined

<table>
<thead>
<tr>
<th>Uncertainty scenario</th>
<th>$\kappa_\Lambda$ 68% CI</th>
<th>$\kappa_\Lambda$ 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>No syst. unc.</td>
<td>[0.7, 1.4]</td>
<td>[0.3, 1.9]</td>
</tr>
<tr>
<td>Baseline</td>
<td>[0.5, 1.6]</td>
<td>[0.0, 2.5]</td>
</tr>
<tr>
<td>Theoretical unc. halved</td>
<td>[0.3, 2.2]</td>
<td>[−0.3, 5.5]</td>
</tr>
<tr>
<td>Run 2 syst. unc.</td>
<td>[0.1, 2.4]</td>
<td>[−0.6, 5.6]</td>
</tr>
</tbody>
</table>
Updated projections for HL-LHC

Charting the Higgs potential with pair-production of Higgs bosons at the ATLAS experiment

CAP 2024 [27-31 Mar 2024]

<table>
<thead>
<tr>
<th>Uncertainty scenario</th>
<th>( \kappa_\lambda ) 68% CI</th>
<th>( \kappa_\lambda ) 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>No syst. unc.</td>
<td>([-0.3, 0.3])</td>
<td>([-0.5, 0.6])</td>
</tr>
<tr>
<td>Baseline</td>
<td>([-0.4, 0.4])</td>
<td>([-0.8, 0.9])</td>
</tr>
<tr>
<td>Theoretical unc. halved</td>
<td>([-0.6, 0.7])</td>
<td>([-1.1, 1.6])</td>
</tr>
<tr>
<td>Run 2 syst. unc.</td>
<td>([-0.7, 0.8])</td>
<td>([-1.4, 2.0])</td>
</tr>
</tbody>
</table>

ATLAS Preliminary
\( \sqrt{s} = 14 \text{ TeV}, 3000 \text{ fb}^{-1} \)

\( HH \rightarrow b\bar{b} \gamma \gamma + b\bar{b} \tau^+ \tau^- + b\bar{b}b\bar{b} \)

Projection from Run 2 data
Asimov data (\( \kappa_\lambda = 0 \))
Resonant interpretation

Resonant upper limits

- BSM models also predict possible heavy resonances decaying to HH
  - Re-optimised analyses to target these scenarios.
- Complementarity between channels allow to obtain optimal exclusion across $m_X$.
- No statistically significant excess found: largest excess at $m_X = 1.1$ TeV, with local (global) significance of 3.2σ (2.1σ).
Combination p-value

Additional material (resonant)

**ATLAS** Preliminary

$\sqrt{s} = 13$ TeV, $126 - 139$ fb$^{-1}$

Spin-0

Local $p_0$-value

$m_X$ [GeV]
Combination acceptances vs $\kappa_\lambda$

Partial Run 2 combination (36 fb$^{-1}$)

Full Run 2 combination
**$\kappa_\lambda$ constraints at future colliders**

*arxiv:2209.07510*

<table>
<thead>
<tr>
<th>collider</th>
<th>Indirect-$h$</th>
<th>$hh$</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>HL-LHC</td>
<td>100-200%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>ILC$_{250}$/C$^3$-250 [50, 51]</td>
<td>49%</td>
<td>–</td>
<td>49%</td>
</tr>
<tr>
<td>ILC$_{500}$/C$^3$-550 [50, 51]</td>
<td>38%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>CLIC$_{380}$</td>
<td>50%</td>
<td>–</td>
<td>50%</td>
</tr>
<tr>
<td>CLIC$_{1500}$</td>
<td>49%</td>
<td>36%</td>
<td>29%</td>
</tr>
<tr>
<td>CLIC$_{3000}$</td>
<td>49%</td>
<td>9%</td>
<td>9%</td>
</tr>
<tr>
<td>FCC-ee</td>
<td>33%</td>
<td>–</td>
<td>33%</td>
</tr>
<tr>
<td>FCC-ee (4 IPs)</td>
<td>24%</td>
<td>–</td>
<td>24%</td>
</tr>
<tr>
<td>FCC-hh</td>
<td>–</td>
<td>3.4-7.8%</td>
<td>3.4-7.8%</td>
</tr>
<tr>
<td>$\mu$(3 TeV)</td>
<td>–</td>
<td>15-30%</td>
<td>15-30%</td>
</tr>
<tr>
<td>$\mu$(10 TeV)</td>
<td>–</td>
<td>4%</td>
<td>4%</td>
</tr>
</tbody>
</table>

**TABLE IX**: Sensitivity at 68% probability on the Higgs cubic self-coupling at the various future colliders. Values for indirect extractions of the Higgs self-coupling from single Higgs determinations below the first line are taken from [2]. The values quoted here are combined with an independent determination of the self-coupling with uncertainty 50% from the HL-LHC.